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THE RELATIONSHIPS BETWEEN TROPICAL CYCLONE TRACKS AND LOCAL SST OVER THE WESTERN NORTH PACIFIC

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Abstract: Tropical Cyclone (TC) tracks over the western North Pacific (WNP) during 1949–2007, obtained from China Meteorological Administration/Shanghai Typhoon institute, are classified into three track types. These types are the main pathways by which TCs influence the coast of East Asia. The relationships between local sea surface temperature (SST) in WNP and TC tracks are revealed. Results show that the local SST plays an important role in TC tracks, though the relationships between local SST and the frequencies of different TC tracks are very dissimilar. The local SST has significant positive correlation with northwest-path TCs, and negative correlation with recurving-path TCs. However, the west-path TCs do not have statistically significant relationship with the local SST. The upper sea temperature anomalies which influence TC tracks last about six months before TC occurrence. Further analysis indicates that the ocean conditions influence TC tracks by modifying the atmospheric circulation, and then the modified atmospheric circulation can affect TC's genesis location and motion.

Key words: tropical cyclone track; western North Pacific; SST

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1 INTRODUCTION

Tropical cyclone (TC) is among the most devastating and damaging weather phenomena affecting humankind, and the TC track anomaly has a large socioeconomic impact on many countries. The tracks of TCs were very abnormal in 2004: an unusually large number of typhoons hit Japan whereas few landfalling typhoons affected the south of China. In the following year 2005, typhoon Matsa, Khanun, Talim attacked the east of China and caused heavy casualties and economic losses. Goldenberg et al.[1] noticed that the damage from TCs is closely related to the landfall location, with damage more serious if landfall occurs in developed areas. The track forecasting is one of the most important aspects of TC prediction, since small differences in the tracks can lead to different landfall and impact regions. Climatological changes of TC tracks are of great importance to both the lives and economy in the coastal regions of East Asia[2].

In general, a TC that forms over the western North Pacific (WNP) takes one of the three typical tracks: two moving straight, either westward or northwestward, and the third northeastward while recurving[2]. Straight-moving typhoons mainly influence the Philippines, southern China, and Vietnam, whereas recurving typhoons occasionally threaten Japan, Korean Peninsula, and northern China[3]. Classifying the TC tracks over WNP to clusters in detail, Camargo et al.[4] found that both the frequencies and impact regions vary considerably with different clusters. In addition, the TC tracks exhibit large variability on different time scales, including intra-seasonal (Harr and Elsberry[5]), inter-annual (Chan and Shi[6]; Xie et al.[7]) and inter-decadal variability (Matsuura et al.[8]; Ho et al.[9]; Wu et al.[10]).

Considering the importance of TC tracks in tropical cyclone forecasting, great efforts have been made to explore the factors that affect TC tracks[11, 12]. A predominant factor in determining TC's motion is the steering flow of surrounding large-scale atmospheric circulation[5, 13, 14]. Since the primary source of energy for TCs is the heat transferred from the ocean to the atmosphere, the air-sea interaction modifies the environmental flow (Wang et al.[15]), and in turn the modified flow influences TCs' motion[12, 13].

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One of the important conditions for TC genesis is the ocean with temperature at least 26° C in the upper 60 m (Gray[16]), while the TC genesis location is thought to have large influence on its subsequent track (Wu and Wang[2]; Jiang and Perrie[17]). Chen and Huang[18] indicated that more TCs affect China when the WNP warm pool is warmer.

The relationship between TC activity and SST has been well studied with regard to how SSTs influence TC frequency and intensity[19-21]. However, possible impacts of the SST variation on TC tracks are not clearly illustrated. In this study, we focus on TC tracks and the SSTs in WNP where the TCs are active. In order to illustrate the local SST variations in association with different TC tracks, we classify the TC according to its real tracks and address the following questions: Do TC tracks change with the local SST variation? How does the local SST influence TC tracks?

The paper is organized as follows. The datasets and an objective classification methodology are described in the next section. In section 3, the relationships between TC tracks and SSTs are studied in detail, followed by further discussion on how the local SSTs impact TC tracks in section 4. Main conclusions and discussion are summarized in the last section.

2 DATASETS AND METHODS

2.1 *Data*

The best-track dataset for tropical cyclones in the western North Pacific is from China Meteorological Administration/Shanghai Typhoon Institute (CMA-STI)[1]. The dataset contains the locations and intensities of TCs at 6-h intervals from 1949 to 2007. Only tropical cyclones with lifetime more than 48 hours and at the intensity of tropical storm or beyond, which include tropical storms and typhoons, are incorporated in the present study. TCs to the east of 150°E are not included owing to their less impact on the east coast of Asia.

The following datasets are also used: monthly atmospheric data with 2.5° ×2.5° resolution for the period of 1949–2007 from the US National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset (Kalnay et al.[22]; Kister et al.[23]); monthly sea surface temperature on 1° ×1° gridpoints from HadSST2 dataset (Rayner et al.[24]). Here we also utilize the subsurface sea temperature data from 1955 to 2003 edited by the Scripps Institution of Oceanography at University of California, San Diego (hereafter referred to as SIO). The data have a reso1ution of 2° latitude by 5° longitude from surface to 400 m in depth in the ocean[2].

2.2 *Methods for the TC classifications*

In this paper, the TC tracks are classified by their real tracks. Details are described as follows. For Northwest Pacific, most of the TCs either recurve or move straight according to the shape of their tracks, while just a few TCs follow complex, complicated or looping tracks; as these tracks are abnormal and occur by complicated forming mechanisms, they are not taken into account in this study.

Only the recurving tracks meeting the following qualifications are considered in the recurving cluster. Before getting to their westernmost point, known as the recurving point, these TCs have lasted for more than 48 hours, distinguishing themselves from those that take a short and west track before shifting northward or northeastward and generally look more like straight-movers.

Most of the straight-movers are moving from the east to the west. The slope *k* of TC track from the genesis to the extinction location is employed to determine the track-types of straight-moving TCs. If the arctangent of *k* is in the range of $(\frac{7\pi}{8},\frac{9\pi}{8})$, this TC is clustered into the west-path TCs. If the arctangent of *k* belongs to $(\frac{5\pi}{8},\frac{7\pi}{8})$, it is called the northwest-path TCs. TCs are merged into the north-track and northeast-track when the arctangent of *k* is in the range of $(\frac{3\pi}{8},\frac{5\pi}{8})$ and $(0,\frac{3\pi}{8})$, respectively. For the northeast-track and north-track TCs, the number is small, only about one per year, therefore these two types of track are not considered in this study.

According to the above simple objective classification of TC tracks over WNP, three main types of TC track, including the northwest, recurving and west paths, are obtained. The number of TCs in the three clusters is 219, 494 and 420 respectively, which covers 71% of the TC total in WNP during the period 1949–2007.

The clustered TC tracks of the three types in 1949 to 2007 are shown in Fig. 1. The impact regions of TCs in the three tracks are in agreement with the results of Wu et al.[10], which are obtained by the TC occurrence frequencies on each grid mesh of 2.5° × 2.5°. The formation of TCs (shown in Fig. 1) mainly occurs to the east of the Philippines and in the South China Sea. The northwest-track TCs, which generate

[1] Available at http://www.typhoon.gov.cn

[2] Visit http://jedac.ucsd.edu/DATA_IMAGES/index.html

in relatively western areas and move northwestward, mainly have impacts on the southeast coast of China and even the Korean Peninsula. The recurving-track TCs, which form to the east of the Philippines and travel westward near the island of Taiwan before recurving northeastward, may affect the Korean Peninsula, Japan and the east coast of China. The west-track TCs mainly occur to the south of 25° N. The west-track TCs are somewhat similar to the northwest-track TCs, but the former is typically longer-lived, located farther to the south, and confined to a long and narrow strip.

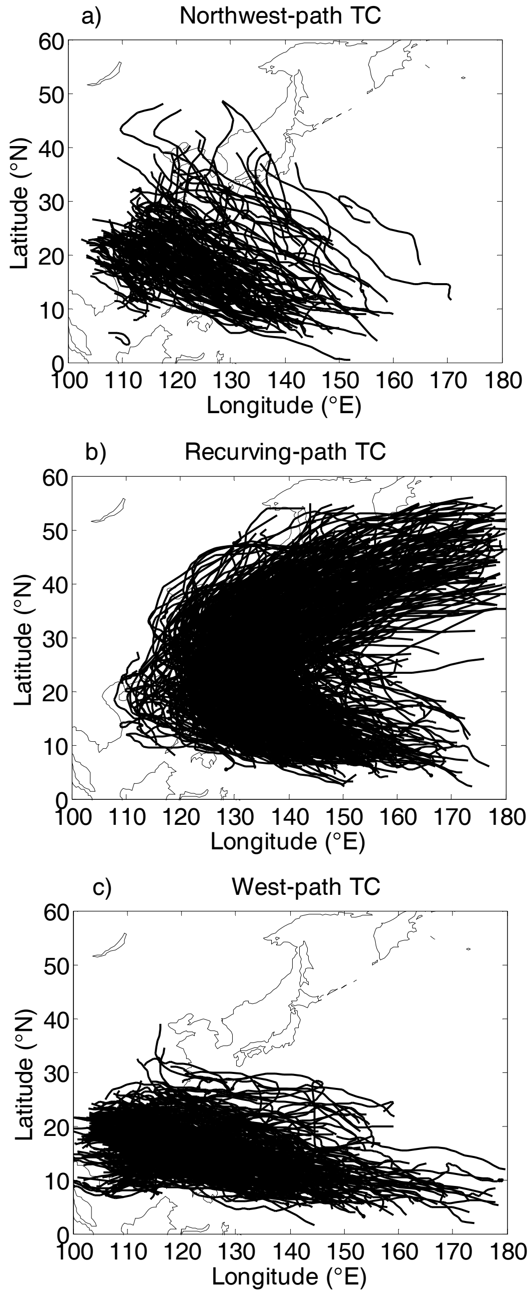

Fig. 1. Tracks over the western North Pacific during the period of 1949–2007. a: northwest; b: recurving; c: west

3 RELATIONSHIPS BETWEEN TC TRACKS AND LOCAL SST

Wavelet analysis indicates that the TC frequencies in the three tracks vary mainly at the inter-annual scale of less than 8 years (figure not shown). Therefore, a high-pass filter, retaining the less-than 8-year variations only, is applied to the TC yearly frequencies and monthly SSTs from Hadley Center. The relationships between the TC frequencies and SSTs at inter-annual scales are shown in Fig. 2. The dark (light) shaded areas indicate significantly positive (negative) correlation at the 90% confidence level.

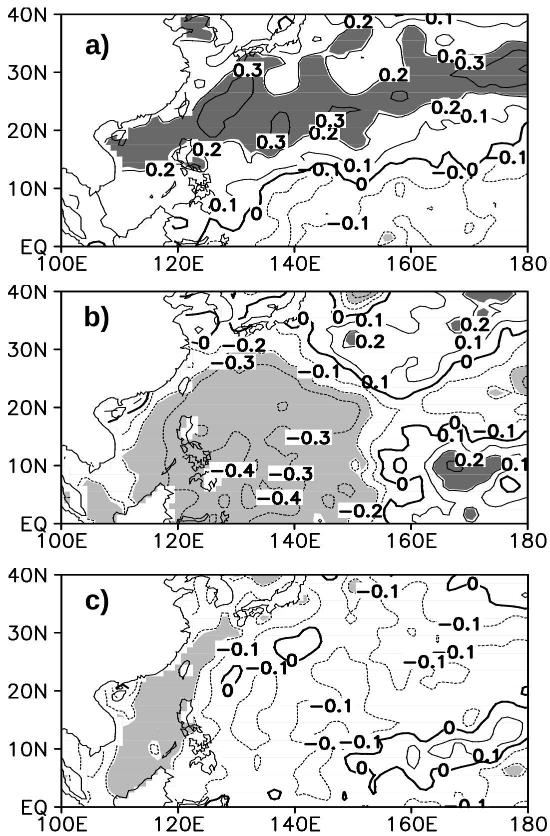

Fig. 2. The inter-annual correlation between TC frequency and SST by tracks, the dark (light) shaded areas are positive (negative) significant at the 90% confidence level. a: northwest; b: recurving; c: west

The frequencies of northwest-track TCs are positively correlated with the SSTs around 10–40° N in the WNP. The correlations between the recurving TC frequencies and SSTs are negatively significant to the west of 160° E in the WNP. There are no significant correlations between the west-path TCs and SSTs in the WNP, except for the negative correlation in the South China Sea.

The SST in the WNP plays an important role in TC track changes, especially when the TC takes a northwest or recurving path. When the local SST is high (low), the TC is more likely to take a northwestward (recurving) track. These opposite correlations mainly stem from the anti-correlation between northwest-track and recurving-track TC frequencies (-0.26). However, the frequency of the west-path TCs has no significant coherence with the local SST at inter-annual scales. Obviously, the local SST has distinct effect on TCs with different track-paths. The SST over the area of 110–140° E, 10–30° N, which is mainly an active region of TCs, has important effect on TC tracks. This area is taken as the local key region of the WNP.

The ocean is a huge energy storage, whose impact on atmospheric circulation is relatively slow and continuous. To determine whether the effect of local SST on TC activity is continuous and how long it lasts, the lead-lag correlation between SST in the key region and the TC frequencies in the three types are calculated (Fig. 3). Note that in this paper, the relationships between the leading SST and TC tracks are focused, which present the influence of SST on TC tracks. It is shown that significantly positive SST appears and leads the northwest-path by about six months, while negative SST appears and leads the recurving-path by about five months. The leading SST has negative correlation with the west-path TCs, but the relationship is not significant.

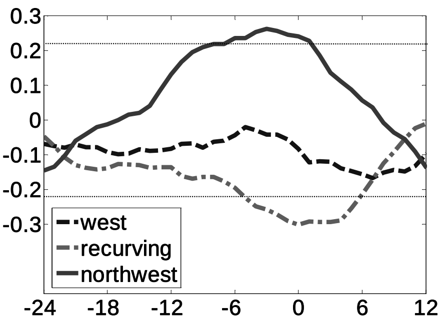

Fig. 3. The lead-lag correlation between TC frequency and SST in key region (10–30° N, 110–140° E), the negative (positive) number of the abscissa means the months which SST leads (lags) the TC frequneces, the dotted lines are the 90% confidence levels.

In addition to the surface condition of the ocean, its upper layer has also large effect on TCs. The lead-lag correlations between the subsurface sea temperatures and TC tracks are shown in Fig. 4. The ordinate is the depth of the ocean, the abscissa is the lead months (as shown in Fig. 3), and the dark (light) shaded areas are in significant positive (negative) correlation at the 90% confidence level.

Beside SST significantly leading the northwest-path TC frequencies, significantly positive correlation between the leading sea temperatures and northwest tracks can be found even at the depth of 120 m (Fig. 4a), which is around the bottom of the mixed layer. The leading correlations with recurving-path TC frequencies are significantly negative in the subsurface layer, but at shallower depths (Fig. 4b). The west-path TCs, as shown in Fig. 4c, are not significantly correlated with the ocean temperature, which is also consistent with Fig. 3c. It indicates that the TC tracks have significant relationship with the subsurface temperature in the ocean. For the three different TC tracks, their relationships with the ocean thermal state differ distinctly.

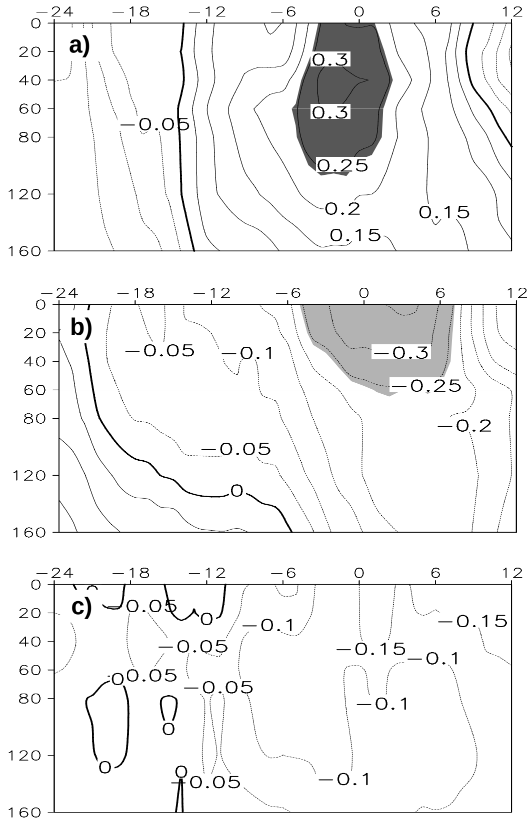

Fig. 4. The deep-lag diagram of the lagged correlation coefficients between TC frequency and sea temperature in the key region (10–30° N, 110–140° E), the negative (positive) number of the abscissa means the months which SST leads (lags) the TC frequneces, dark (light) shading areas are positive (negative) significant correlation at the 90% confidence level. a: northwest; b: recurving; c: west

The results show that the TC track frequencies are closely related to the thermal state of the local ocean in WNP, and the relationships are dissimilar in different track-paths. The local SST has significantly positive (negative) correlation with the northwest-path (recurving-path) TCs about six months before the TC occurs. These significant correlations not only exist on the sea surface, but also in the subsurface ocean. However, the west-path TCs have no significant relationship with local SST.

4 MECHANISM FOR LOCAL SST IMPACT ON TC TRACKS

Shay et al.[25] noticed that a phase-lock exists between the upper ocean and atmospheric processes during fast development of the TC. The ocean and atmosphere should not be isolated. The distribution pattern and thermal state of local sea temperature greatly influence TC genesis and track. The ocean affects the atmospheric circulation, and then the modified atmospheric circulation exerts an impact on TCs. Since the west-path TC has no significant relationship with local SST, we only discuss how and why the local SSTs have an impact on the northwest and recurving TC tracks in this paper.

Based on the interannual variability of northwest-track and recurving-track TCs, composite SST anomalies (SSTA) in the months with more northwest-path or recurving-path TCs, in which monthly TC numbers are more than 1.5 times standard deviations above the mean, are constructed (shown in Fig. 5). When northwest-path TCs are above the mean, a positive SST anomaly can be found to the west of 160° E (Fig. 5a). Along with the positive SST anomaly, the reduced Outgoing Longwave Radiation (OLR) can be found, which indicates that strong convective activities are favorable for TC formation in that region. The composite SSTA of the recurving-path TCs is generally opposite in pattern to that of the northwest-path TCs (Fig. 5b), with the negative anomaly center in the South China Sea and the western Philippine Sea. The anomalous OLR pattern associated with the negative SST anomaly can be found to the east of the Philippines. It means that strong convection shifts eastward, resulting in TCs genesis in farther east areas.

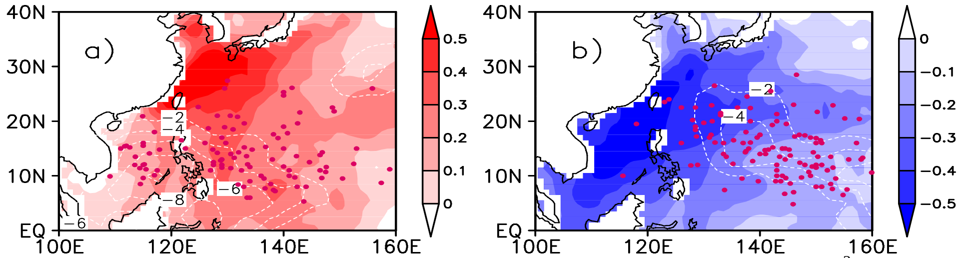

Fig. 5. Composite SST anomalies (shaded, unit: ° C) and OLR anomalies (contours, unit: W m^2) in which months the TC number is more than 1.5 times standard deviations above the mean. The dots indicate the TCs genesis locations. a: northwest; b: recurving

Another important factor in determining TC's motion is the steering flow of the surrounding large-scale atmospheric circulation (Chan[13]). It is necessary to investigate whether and how the SST anomaly affects the atmospheric circulation above.

The month in which TCs occur simultaneously is defined as month 0, with the preceding month being defined as the leading month. The SSTA variations from the leading two to zero months are shown as the shaded part in Fig. 6. The composite SSTA of the northwest-path TC already has positive anomaly to the west of 160° E in the leading two months, the abnormal positive values are increasing gradually and the anomalous center is located near the coast of China's mainland in the simultaneous month. An anomalous anticyclonic circulation is located over the location where there is positive anomalous SST that enhances gradually, accompanied by positive SSTA variation. The composite SSTA variation of the recurving-path TC has an opposite pattern approximately (Fig. 6b), but with anomalously cyclonic circulation located over the negative anomaly center in the South China Sea. Corresponding to the persistent SST anomalies, the anomalous atmospheric circulation also experiences an adjusting process.

The large-scale atmospheric circulation may interact with the TC circulation when the TC is active. To ignore the impact of the TC circulation on atmospheric circulations, we composite the 500-hPa wind anomalies of the days just one week before each TC occurrence (figure not shown). Results show that an anticyclonic (cyclonic) circulation anomaly—with the center located near 30° N (20° N)—already exists even before the northwest-path (recurving-path) TCs occur, and these anomalies have similar patterns with those of Fig. 6a (Fig. 6b). The persistent atmospheric circulation anomalies will affect TC tracks. The previous analysis indicates that these atmospheric circulation anomalies are related to SSTA, and the persistent SSTA and atmospheric circulation anomalies can provide a large-scale background favorable for certain TC tracks. Hence, to illustrate how the SST anomaly affects the above atmospheric circulation and then influences the TC tracks, the simultaneous month is analyzed as an example.

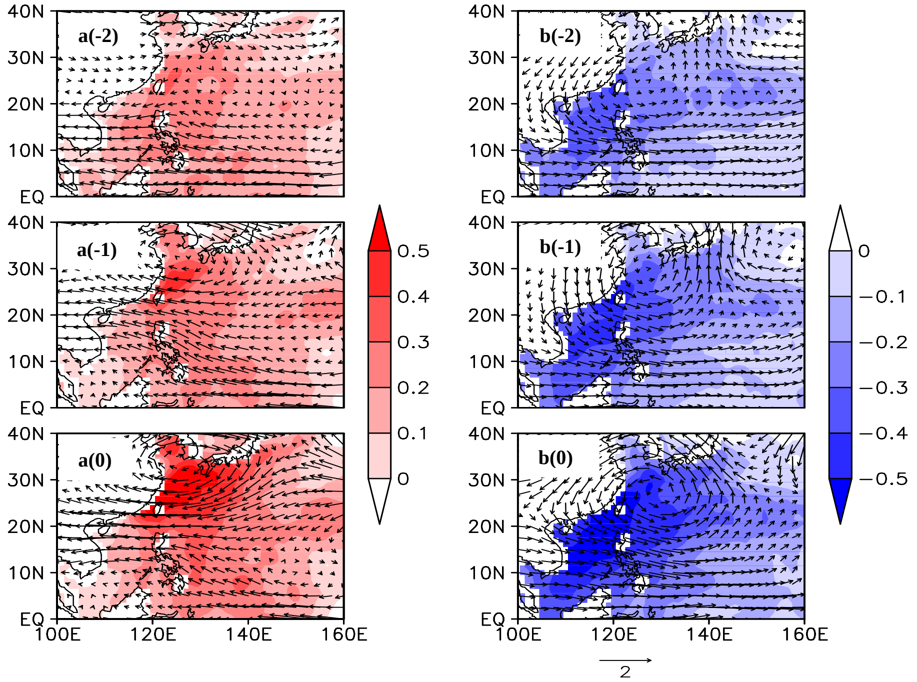

Fig. 6. Same as Fig.5, but for SST anomalies (shaded, unit: ° C) and 500-hPa wind anomalies variation (vector, unit: m s^{-1}). The number on the top left corner indicates the leading month of TC occurrence. a: northwest; b: recurving

The SST anomaly can result in the anomaly of air temperature above the sea surface, thereby causing the anomalous gradient of temperature in the air. Fig. 7 shows the meridional gradient of temperature anomaly (the shaded zone), which is integrated from the surface to 500 hPa. The center of the positive SST anomaly is located near 30° N in Fig. 6a0. Corresponding to this warm anomaly, there are negative meridional gradients of temperature anomalies to the south of 30° N, and positive to the north (Fig. 7a). Consistent with the cold anomalies shown in Fig. 6b0, the negative (positive) meridional gradients are to the north (south) of 25° N (Fig. 7b).

According to the thermal wind balance, the negative (positive) meridional gradient of temperature can cause easterly (westerly) wind anomaly in the Northern Hemisphere. Wind anomalies at 500 hPa are also shown in Fig. 7 (the vector). In Fig. 7a, anomalous easterly (westerly) flow appears to the south (north) of 30° N, which is consistent with the thermal wind balance. Thus, an anomalous anticyclonic circulation is located over the positive anomalous SST. The anomalous anticyclonic circulation indicates that the western Pacific subtropical high strengthens and extends westward (Fig. 8a). That causes strong southeasterly wind in the region of TC activities to steer TCs in the northwest-path track.

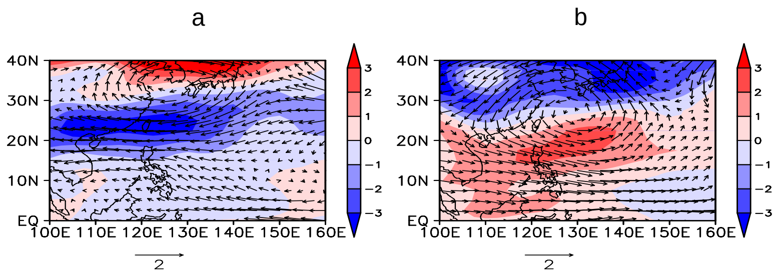

Fig. 7. Same as Fig. 5, but for the meridional gradient of temperature anomaly integrated from the surface to 500 hPa (shaded, unit: °C m^{-1}) and 500-hPa wind anomalies (vector, unit: m s^{-1}). a: northwest; b: recurving

In contrast, in Fig. 7b, the anomalous easterlies and westerlies are south and north of 25° N, respectively. Hence, an anomalous cyclonic circulation is located east of East Asian coastal islands (Fig. 7b, in vector), indicating that the subtropical high weakens and withdraws eastward with the 5860-gpm contour reaching only about 125° E in August (Fig. 8b), which is favorable for TCs to take the recurving-path along the west edge of the subtropical high.

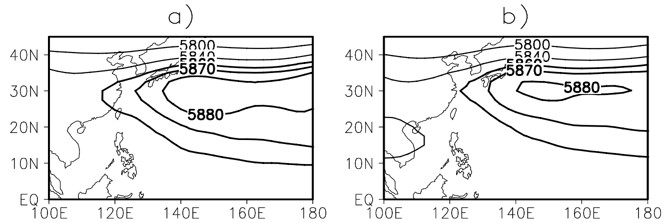

Fig. 8. Composite geopotential height (unit: gpm) at 500 hPa of the Augusts in which the TC number is more than 1.5 times standard deviations above the mean, when most northwest (a) and recurving (b) TCs occur.

5 CONCLUSIONS AND DISCUSSION

Based on the TC track datasets over 1949–2007 from CMA-STI, the TCs in WNP are classified into three types of track according to the TC track shapes. The three types of track are the northwest-path, recurving-path and west-path, respectively, which are the main pathways by which TCs have impacts on the coast of East Asia. The results of our study show that the local SST plays an important role in TC tracks. The relationships between local SST and TC tracks differ from each other. The local SST has significant positive correlation with the northwest-path TCs and negative correlation with the recurving-path TCs. However, the west-path TCs have no statistically significant relationship with local SST. Although the TC track datasets and intensity are considered poorer during pre-satellite years (prior to 1970) (Camargo el al.[4]), the tracks that appear in the dataset are thought to be reliable. We repeated the correlation analysis for 1970–2007 and found that the relationships between TC tracks and local SSTs are essentially the same as those of the pre-1970 time. It implies that the datasets from pre-satellite years will not influence the results significantly. These different relationships between TC tracks and local SST may partly explain some of the previous results that local SST has small impacts on the TC activity when the whole WNP is studied (Chan and Liu[21]; Yumoto and Matsuura[26]).

One of the important results in this study shows that local SST has positive (negative) effect on the frequencies of the northwest-path (recurving-path) TC. Elsner and Liu[3] suggested that the anti-correlation of straight-moving and recurving typhoons hints at a large-scale mechanism for changes in landfall probability and possible mechanisms involving changes in SST. The subsurface ocean, as a whole, has persistent anomalies before the occurrence of TCs. This indicates that the ocean may affect TC tracks by supplying energy to change the atmospheric circulation at first, and then the modified atmospheric circulation influences TC's genesis location and motion. However, the frequency of the west-path TC has no statistically significant correlation with the local SST. The complicated relationship between the west-path TCs and SSTs need to be further studied in the future.

The influence of local SSTs on TC tracks may be considered from two aspects. First, the local SSTs affect the location of convection activity and the monsoon trough, which are extremely favorable for TC genesis. The warm local SST can strengthen the convection and induce the monsoon trough to move westward, which is in favor of TC genesis west of 140° E. By contrast, the cold local SST causes the convection region to shift eastward, thus benefiting TC genesis in further east areas. Second, the local SST anomalies will change the meridional gradient of the atmospheric temperature above and cause thermal wind circulation anomalies, thus modifying the location of the subtropical high and the steering flow, which is important to TC tracks. The anticyclonic thermal wind anomalies caused by warm local SST tend to strengthen the subtropical high, with the subtropical high extending westward. The resultant westward extension affects the steering flow that can cause TCs to be moving northwestward. The cyclonic circulation anomalies caused by cold local SST induce the subtropical high to go eastward, which favors more TCs to recurve northeastward.

Other studies suggested that TC genesis locations have large influence on the subsequent tracks (Wu and Wang[2]). To examine whether diverse TC tracks are related to different TC genesis only, we focus on the region of 130–145° E, 5–20° N, in which there are most genesis of TCs, not only of the northwest-path but also of the recurving-path, as shown in Fig. 5. Monthly SST anomalies associated with the northwest-path and recurving-path TCs generated in the same region of 130–145° E, 5–20° N are composited (Fig. 9). In Fig. 9, positive (negative) SST anomalies with the center located near 30° N (25° N) are found when more northwest-path (recurving-path) TCs occur, and these anomalies have the same patterns with those of Fig. 6. It indicates that the number of northwest (recurving) TCs still have the positive (negative) correlations with local SST, even with TC genesis in the same region. These relationships are mainly due to the steering flow changed by the local SST (as shown in Figs. 7 & 8). This confirms our conclusions that the influence of local SST on the steering flow is also important to TC tracks.

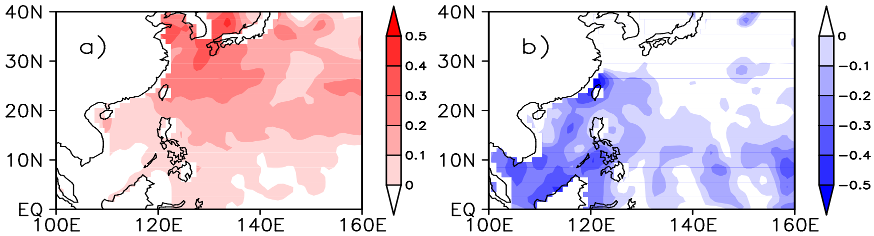

Fig. 9. Composite SST anomalies (shaded, unit: ° C) of the months in which TCs generate over the region of 130–145° E, 5–20° N in Fig. 5, a: northwest; b: recurving

The local SSTs having impacts on TC tracks have persistent anomalies before the TC occurs, which can provide a possibility of using the leading SST anomaly as one of the predictors in forecasting TC tracks. However, in the present study the characteristics of TC tracks and their relationships with SST are based on statistical methods only. In the future, numerical experiments are needed to confirm our conclusions.

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